Flexible Energy Consumption in Smart House's

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Flexible Energy Consumption in Smart House's

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Abstract: The last couple of years more and more non-controllable energy sources, e.g. wind turbines, have been connected to the power grid. This has caused an inefficient energy production and a huge variation in the energy prices. In the near future (10 to 15 years) the amount of non-controllable energy sources will double or more. This again will result in a number of problems: Inefficient energy production, problems with controlling the power grid, the wind turbines have to stop when the wind is optima and so on. The way to overcome these problem is to make the power consumer more flexible, or in other word the consumer have to use the energy when it is available. The main electrical energy consumer in a modern society is buildings and private homes. The amount of electrical energy used in this sector is about 70% of the total electricity consumption. Because of that buildings and private homes has to play an active role in controlling the power grid, and by that mean secure a more efficient and green energy production. If houses and private housholds has to be a part of the solution then it is very important to finde a solusion that minimize the impact on the living comfort. The way to due that is to make an automatic and inteligente house control system that maximize the consumption flexibility based on the energy users behavior with out affection the living comfort. This behavior is of course different from household to household, because of that it is nessasary include an adaptive behavior prediction system. This paper describes a method to make houses flexible based om preknowlages of the user behavior. And calculate the energy flexibility base on simulation for 200000 typical houses in Denmark. The simulations shows that it is possible, based on 200000 houses, to store enough energy to absorb the variation in the production over a time horisont on several hours.

1. INTRODUCTION

In the future the society will more and more be based on electrical energy generated from renewable sources e.g wind turbines, solar panels, wave energy and so on. If these form of renewable energy production should be profitable they have to produce energy when the conditions are right or in other words the production will be govern by a non-controllable source. Because of that the amount of available energy and the place where the energy is generated variate over time and will not be in line with the consumption pattern. This will increase the demands to the power grid (the Smart Grid) and to the flexibility of the consumer. In the last couple of years a lot of recurs effort has been put in to Smart grid. E.g. Herrmann et al. (2008) make a field test with 25 households to investigate the consumer flexibility. The paper shows that it is possible to move op to 50 % during peak loads by givin the consumer an economic incentive to use the waching machine at the right time. Gram-Hanssen (2011) analyse in more ditail the energy consumption in private houses by looking at the effeth of user practice. A number of research projects concerning smart grid. You et al. (2009) describe metodes for Distributed Energy Resources (DER) can take part in the current energy market. other e.g. Caldon et al. (2004) deals with controlling the DER's. Trangbk et al. (2011) looks at the load distribution between the consumers. An other important isue is how to multivate the consumer to use the energy the right way e.g. Caldon et al. (2004) and finaly Brønsted et al. (2010) and Madsen (2009) describe how to design and programm the in-house control system. This paper's will focus on consumer flexibility. This flexibility should be achieved without involving the user and with out compromising the living comfort in the house. This requires that the controlling of the house is done automatize by an in-house control system. The paper analyze the possible flexibility based on the heating system. Other equipment, like washing machines, refrigerators, freezers can be taken in to around and by that mean increase the flexibility.

There is approximately 1,1 mill houses in DK. Many of these residence are heated by electricity either directly or by a heat pump. Beside of that there is approximately 350000 houses based on local oil firing. In the feature most of these oil based heating systems will by exchange by heat pumps. this means that in the feature approximately the half of the houses in DK will be based on electrical heating either direct or by heat pump. The rest will by based on other heating methods like district heating bio-mass and so on.

Figure 1 shows the price on the spot market for the western part of DK from the 9/9 to 15/9 2011. The figure shows that there is high price in the daytime and low price in the late night time from approximately midnight to about 6 in the morning. This period was relative windy over the western part of Denmark, and because of that, the

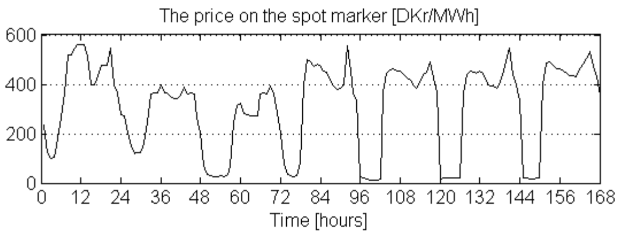

Fig. 1. The spot market price on the western part of Denmark from the 9/9-11 to the 15/9-11.

price shows to be volatile in that period of time. In the feature these volatile prices will be a more normal case then now. This is due to the increasing amount of wind turbines over the coming years. To day the average price volatility over a whole year, are given by a 50% higher price during the dag time then in the night timer. This price volatility shows that there is a economic motivation for botch the power trading companies and the consumer to move the consumption to period with cheap energy. This again requires that it is possible, for the consumer to move the consumption from the day time to the night time. This paper will analyze the possibility for the moving of consumption to the cheap night time, based on a standard house dynamic.

2. METODE

The study of energy flexibility will be based on the conditions in Denmark. This paper will focus on the electric energy used for heating e.g. room heating and heating of the hot water. It is assumed that around 20 % of the private houses are heated by heat pumps or by electricity directly. This lead to the following Simulation assumptions:

- 200.000 households with electricity based heating.
- All households are medium heavy Aggerholm et al. (2005) and have a size of 160 m^2.
- All houses are heated by a floor heating system.
- All households are equip with a 200 l tank for hot water.
- The houses are heated by electricity either direct or indirect by a heat pump with a COP-factor equal to 4. There will be the same number of direct and indirect heated houses.
- The temperature in all rums will be the same.
- The walls and the ceiling will have the same temperature.
- The people living in the houses accept a temperature between 19-21 ^{o}C. With the restriction that the temperature must not be lower than 20 ^{o}C from 19:00 to 22:00.
- After kl 23 or when all rum are empty the room temperature can be lowered to 15 ^{o}C.
- The outside temperature estimated based on an average autumn day with a maximum and minimum temperature given by: 10.5 ^{o}C at 14. and 4.9 ^{o}C at 2. The temperature between these two extremes points is given by a sinus curve.

The heat capacity of the houses: The heat capacity for a medium heavy Danish house is: 120 Wh/(Km^2) i.e. for the 160 m^2 standard house: C_{house} =19200 Wh/K. This can be divided in to a part from the floor and a part from the walls and the ceiling (WC): C_{Floor} = 4800 Wh/K and C_{WC} =14400 Wh/K The heat capacity of water: 4.2 J/(gK) e.i. for the 200 l hot water tank: C_{Water} =233Wh/K The air and the furniture inside the house are calculated as only one heat capacity. The heat capacity of the furniture's is sat to be 20% of the air heat capacity.

The volume-specific heat capacity of air is: c_{Air} = 0.36 Wh/(m3K). If the room height is 2.3 m then the heat capacity of the air and the furniture inside the is given by: C_{AF} =160 m^2*2.3 m * 0.36 Wh/(m3K) *1.2 = 159 Wh/K The heat transfer coefficient between the air and the walls/ceiling is given by: G_{AW} =2.5 W/(m2K) . For the total house with 490 m2 Wall/ceiling total heat transfer is estimated to: G_{AWtot} =1225 W/K. The heat transfer between the floor and the air is estimated to: G_{FA}= 400 W/K; The heat transfer between floor and walls due to heat transfer in the construction is estimated to: G_{FW} =100 W/K The heat transfer between the floor, walls and ceiling is estimated to: G_{outlet} = 160 W/K.

The controlling of the heat system is governed by the behavior of the people living in the house. This behavior result in requirement for room temperature, hot water temperature and the use of hot water as a function of time over the day.

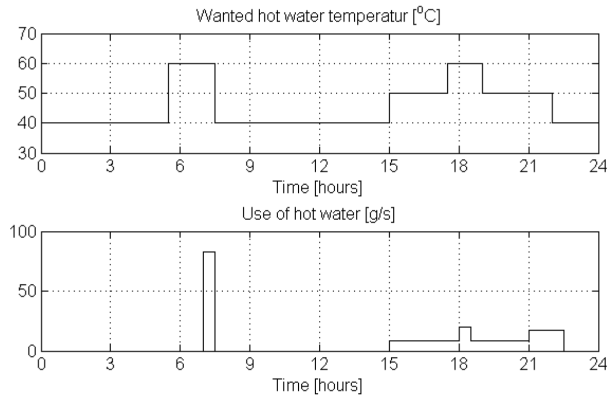

Fig. 2. The desired minimum temperature of the hot water and the estimated use of hot water over 24 hours.

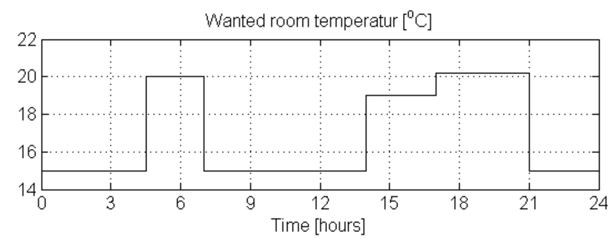

Fig. 3. The desired minimum room temperature.

These requirement for temperature and water use is illustrated on Figure: 2 and figure: 3. This 24 hours standard behavior is used a input to the simulation for all houses and all days. The control of the room temperature are based on a ON/OFF controller with a hysteresis given by 0.2 ^{o}C.

The hot water controller is also a ON/OFF controller here with a hysteresis of 4 ^oC.

The total result of all 200000 houses are found by simulation of one direct heated house and one indirect heated house and then multiplying the energy consumption with result by 100000.

The simulation is based on a 3rd order model as shown on figure 4. There is three main heat capacity in the house namely the floor, the walls/ceiling, and the inside of the house e.g. the air, the furnitures and so on. The main heat transfer is from the floor to the air and from the air to the walls/ceiling. Beside that there is a direct heat transfer from the floor to the walls. The energy inlet is placed in the floor witch is the normal case for all new houses in DK. The energy loss is manly from the walls/ceiling and from ventilation of the house.

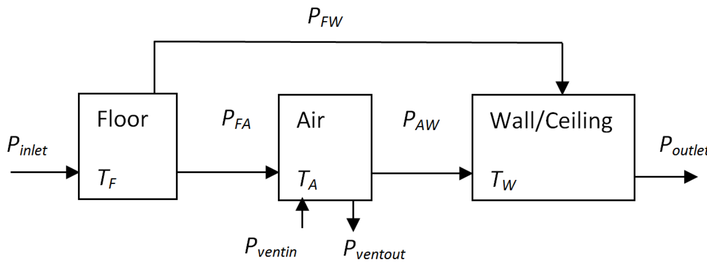

Fig. 4. The house model.

Where: P_{inlet} are the heating effect.
P_{ventin} are the supplied effect from the ventilation in
$P_{ventout}$ are the supplied effect from the ventilation c
P_{outlet} are the given off effect from the house.
P_{FA} are the effect from the floor to the air.
P_{AW} is the effect from the air to the walls and ceilin
P_{FW} are the effect from the floor to the walls.
T_F are the temperature of the floor.
T_A are the temperature of the Air.
T_W are the temperature of the walls/ceiling.

Energy balances:
For the floor:

$$C_{\text{Floor}} \frac{\partial T_F}{\partial t} = P_{inlet} - P_{FA} - P_{FW} \tag{1}$$

For the Air:

$$C_{\text{Air}} \frac{\partial T_A}{\partial t} = P_{FA} - P_{AW} + P_{ventin} - P_{ventout} \tag{2}$$

For the Walls/Ceiling:

$$C_{\text{W}} \frac{\partial T_W}{\partial t} = P_{AW} + P_{FW} - P_{outlet} \tag{3}$$

Where:

$$P_{FA} = G_{FA}(T_F - T_A)$$
$$P_{FW} = G_{FW}(T_F - T_W)$$
$$P_{AW} = G_{AWtot}(T_A - T_W)$$
$$P_{\text{outlet}} = G_{\text{outlet}}(T_W - T_o)$$

$$P_{\text{ventin}} = \dot{M}_v c_{\text{Air}} T_o$$
$$P_{\text{ventout}} = \dot{M}_v c_{\text{Air}} T_A$$

3. RESULTS

The result are dived into three cases.

(1) The room temperature, the hot water temperature and the hot water use are controlled acordint to the standard behavior. (Fig. 2 and 3).
(2) The room temperature are set to to 20.1 ^{o}C and the hot water temperature are set to to 65 ^{o}C. The use of hot water is the same sa in case 1.
(3) The maximum amount of energy are moved to the night time starting at 2:00.

3.1 Case 1:

Figure 5 shows the temperature in the house with heat pump. The temperature in the house with direct heating is simulate the only difference is that the direct heated house have two heat sources one for the hot water and one for the room heating where the heat pump based house only have one heating source e.g. the heat pump. The set point for the controllers is according to the standard behavior. The simulation shows that the main energy consumption is in the morning and in the afternoon. The requirement for room temperature and hot water is the highest in these periods.

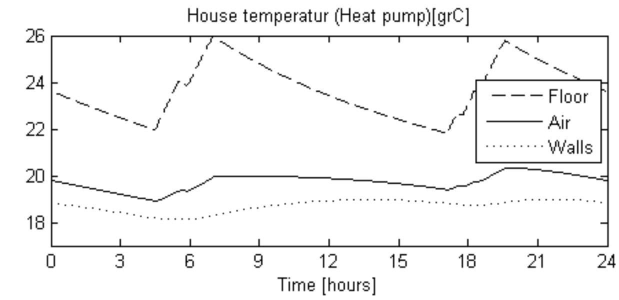

Fig. 5. The temperature in the house with heat pump. The set point for the controllers is according to the standard behavior. (Fig. 2 and 3).

Figure 6 shows the possible amount of energy that it is possible to store in the house (E_s) during 24 hours with out violating the comfort requirement. E_s is calculated based om the heat capacity and the actual temperature in the house. The upper graf is for the house with direct heating and the lower graf is for the house with heat pump. The mean of E_s over the period for the direct heated house is $8.04 \cdot 10^7$ [J]. witch is equal to 22.3 [kWh]. This means that it is possible to store 22.3 [KW/H] in mean. The maximum of E_s is approx. $11 \cdot 10^7$ [J] and the minimum is approx. $5 \cdot 10^7$ [J]. The mean over the period for the house with heat pump is $1.86 \cdot 10^7$ [J]. witch is equal to 5.2 [KW/H]. The maximum is approx. $2.7 \cdot 10^7$ [J] and the minimum is approx. $1.3 \cdot 10^7$ [J].

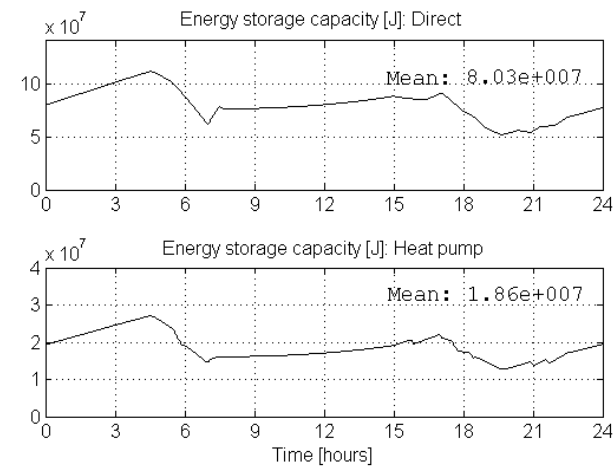

Fig. 6. The amount of energy possible to store in the house with out violating the comfort. (Known behavior)

3.2 Case 2:

If the standard behavior i unknown or unused, then the temperature will be based on constant setpounts. The setpoint for the room temperature is sat to 20.1 ^{o}C, This is due to the requirement: Not lower than 20 ^{o}C from kl 19 to kl 22. The setpoint for the hot water is set to 65 ^{o}C for the hot water. Figure 7 shows the possibility of storing energy in a house in this case. The mean of E_s for the direct heated house is $4.86 \cdot 10^7$ [J]. The mean for the house with heat pump is $1.2 \cdot 10^7$ [J]. This shows that it is possible to increase energy storages capacity (E_s) in a house by take advantage for a known behavior of the people living in the house. The increase in mean is approx. 60%. In the night time where energy prices are low the increase is approx. 125 %.

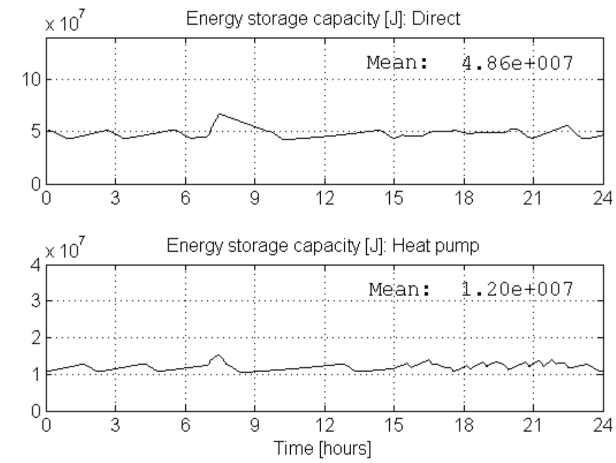

Fig. 7. The amount of energy possible to store in the house with out violating the comfort. (Unknown behavior)

3.3 Case 3:

In this case the house is controlled according to the standard behavior. At 2:00 the energy storages capacity (E_s) is calculated. The amount of energy that is possible to put in to the house is given by $E_t = E_s + E_h$ where E_h is the energy necessary for holding the room temperature constant level e..g E_h is equal to the heat loss from the house. From 2:00 the heating system is running at its maximum until This energy E_t is used. Figure 8 show the temperature in the house. The temperature is start rising approx. 3:00 this is because the hot water as higher priority then room heating. The amount of energy that is possible to move is for the direct heated $1.3 \cdot 10^8$ [J] and $3.2 \cdot 10^7$ [J] for the hear pump based house. The total energy consumption for heat over 24 hours is for the direct heated: $2.55 \cdot 10^8$ [J] and for the Heat pump based house $6.42 \cdot 10^7$ [J]. This means that approx. the half of the energy consumption for heat can be moved to a period from (in this case) 2:00 to approx. 5:00. If 100000 houses with direct heating and 100000 houses with heat pump are add together the total storage capacity will be 4.5[GWh] ore approx. This value is more or less the same as the total electrical energy consumption for one hour in Denmark. In other word if the energy store is due to absorption of the variation in the production, the storage capacity is big enough to overcome several hours over/under production.

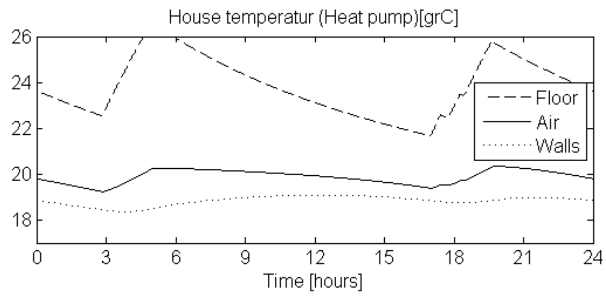

Fig. 8. The temperature in the house with heat pump. The set point for the controllers is according to the standard behavior. (Fig. 2 and 3).

In table 1 the total energy consumption over a 24 hours period is shown. Case 1 and case 3 shows the different between the total energy consumption with out and with energy storages in the house. Or in other word the efficient of using houses as energy store. The energy consumption with out energy storage is for the direct heated: $2.55 \cdot 10^8$ [J] and for the Heat pump based house $6.42 \cdot 10^7$ [J] and the energy consumption with energy storage is for the direct heated: $2.58 \cdot 10^8$ [J] and for the Heat pump based house $6.66 \cdot 10^7$ [J]. For the direct heated house the energy loss according to energy storages is $0.03 \cdot 10^8$ [J] witch gives a storage efficiency of: 98% For the heat pump based house the energy loss according to energy storages is $0.24 \cdot 10^7$ [J] witch gives a storage efficiency of: 92% The other result divided from table table 1 is that it is a important to use the knowledge about the behavior of the people living in the house. Case 1 and case 2 shows that it is possible to lower the energy consumption when using the behavior knowledge by approx. 10% and as mensiont ealigere also increese the energy storage capacity by approx. 125 % in the night time.

Type	Case 1	Case 2	Case 3
Direct	$2.55 \cdot 10^8$	$2.84 \cdot 10^8$	$2.58 \cdot 10^8$
Heat pump	$6.42 \cdot 10^7$	$7.04 \cdot 10^7$	$6.66 \cdot 10^7$

Table 1. The energy used over 24 hours [J]

4. CONCLUSIONS

In this paper, a simple 3rd order model of at medium heavy and medium size house is developed. Based on this model and knowledge about behavior of the people living in the house the possible energy flexibility and energy storage efficiency is analyzed. The result shows that it is possible to move approx. the half of the energy consumption for heat to the cheap period in the night time and that the efficiency of the energy storage is more than 90 %. If 20 % of the danish houses are equipt with either heat pump or direct el-based heating then it is posible to move an amount of energy equal to one hour of the total eletrical energy consumption in Denmark. This dehavior optimiced flexibility and energy storages management requres an intelligente house control system that is able to control the house and dynamical estimate the behavior of the people living in the house.

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